Acoustic Propagation in Continental Shelf Break and Slope Environments FY11 Annual Report

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LONG-TERM GOALS

The long-term goal of the research is to increase the physical understanding of acoustic propagation in continental shelf and slope environments in the 50-4000 Hz band. This includes both the physics of the seabed and the coupling to physical mechanisms in the water column in complex range- and azimuth-dependent littoral waveguides.

OBJECTIVES

There were two main objectives of the current research. The first objective was to continue to refine and improve on a statistical inference approach and to apply the method to the analysis of acoustic data taken in the Shallow Water 2006 (SW06) experiment. The second objective was to develop and test a new coupled mode approach that will serve as the basis for an advanced seabed attenuation analysis of SW06 data.

APPROACH

The method applied for the first objective was to continue to use data obtained from the SW06 experiment to test hypotheses made for statistical inference of waveguide parameters. There is ongoing collaboration with Mr. Jason Sagers on (1) identifying mode-coupling effects in SW06 data and (2) performing statistical inference in environments with significant range and temporal variability. The theoretical approach to statistical inference is based on maximum entropy. Using acoustic data measured in SW06 where the source levels are known to within a small uncertainty acts as a means of validation of the statistical inference method. Further, such data can be used to "push the range envelope" of an inversion approach based on coherent full-field processing.

The method applied for the second objective was to develop a 1-way propagation model that includes the coupling to the backward propagating field. The forward-backward coupling is included with a perturbation approach based on quantum many body methods employed in nuclear theory.

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WORK COMPLETED

The work completed in FY11 includes (1) the completion and testing of a new coupled mode model, (2) introducing a method to validate a statistical inference approach and, (3) demonstrating the possibility of coherent geoinversion over about 350 water depths in a shallow water environment in the 50-250 Hz band.

(1) In an acoustic waveguide spatial inhomogeneities couple the forward and backward propagating modal amplitudes. To address the nature of such coupling the integral equation for the range-dependent modal amplitudes was decomposed into components that satisfy the asymptotic boundary conditions of the free Green's function operator. An equivalent set of equations was obtained by eliminating the components that become the asymptotically backward propagating channels to leave a set of integral equations that describe only the components that become asymptotically the forward propagating channels. The elimination of the components that become asymptotically the backward propagating channels was done at the expense of introducing a nonlocal effective coupling operator. The nonlocal operator contains all the effects of the asymptotically backward propagating field on the asymptotically forward propagating field. An expansion of the effective coupling operator allowed for an investigation of the importance of the coupling and provided a systematic approach to add correction terms to the forward only equation.

(2) A conditional probability distribution suitable for estimating the statistical properties of ocean seabed parameter values inferred from acoustic measurements was derived from a maximum entropy principle. The specification of a second-order expectation value constrains the maximization of an entropy functional. This constraint determines the sensitivity factor (β) to the data-model error function of the resulting probability distribution. From the conditional distribution, marginal distributions for individual parameters can be determined from integration over the other parameters. The approach is an alternative to obtaining the posterior probability distribution without an intermediary determination of the likelihood function followed by an application of Bayes' rule. The expectation value that specifies the constraint was determined from the values of the error function for the model solutions obtained from a sparse number of data samples. The method was applied to ocean acoustic measurements taken on the New Jersey continental shelf (SW06). The marginal probability distribution for the values of the sound speed ratio at the surface of the seabed can be validated with the marginal distributions for the source levels of a towed source data sample where the true values of the source levels were known to within an uncertainty of about 1 dB.

(3) Tow data in the 50-250 Hz band from the SW06 measurements were recorded over a spatial scale of about 25 km (~ 360 water depths). These data show signs of coherent structure over the full spatial scale in a manner that suggest coherent matched field geoacoustic inversion might be successfully performed over large distances. Normally, geoacoustic inversion is limited to short ranges because unknown inhomogeneities (for example range dependent sound speed profiles) limit the ability to successfully perform coherent matched field processing. Using the measured source levels and allowing for a 2 dB uncertainty in the prior source level distributions, inversions for seabed parameters in the first sediment layers are preformed using coherent transmission data out to about 25 km.

RESULTS

(1) Figure 1 shows 2-D~waveguide testcases with three bottom bathymetry profiles having an irregular succession of hill-shaped features of variable heights. The background depth of the waveguide is 285 m. The three bathymetry profiles, case A, case B, and case C, have average hill heights of about 4, 8,

and 13 m, respectively. The coordinates x and z refer to horizontal range and depth, respectively. The total number N_x of horizontal range mesh points is 2192 with a spacing of 6 m. The depth mesh spacing is 1 m. The surface and bottom boundaries are pressure release and rigid, respectively. The sound speed in the water column (1500 m/s) is a constant in z and x, and there is zero absorption. Also the density in the water is a constant and set to 1 g/cm^3. For such a waveguide the horizontal wavenumber mode eigenvalue $k_n(x)$ is either purely real (propagating part of modal spectrum) or purely imaginary (evanescent part of modal spectrum). Over a horizontal range of about 10 km there are 33 hills. The *left* and *right* sides of the waveguide have asymptotic regions. The right asymptotic region is x > 10.5 km. The source, located at z=50 m, is in the left side asymptotic region. At 10 Hz there are four propagating modes over the full horizontal range and 25 range mesh points per wavelength. The analysis of cases A, B, and C first considers only the propagating part of the modal spectrum. Additional computations for these three cases are made to quantify the effect of mode 5 which is evanescent throughout the entire horizontal range scale. Finally, case D is the same as case B, except that the background depth of the waveguide is reduced from 285 to 265~m. This has the effect that mode 4 becomes evanescent over portions of the inhomogeneous region.

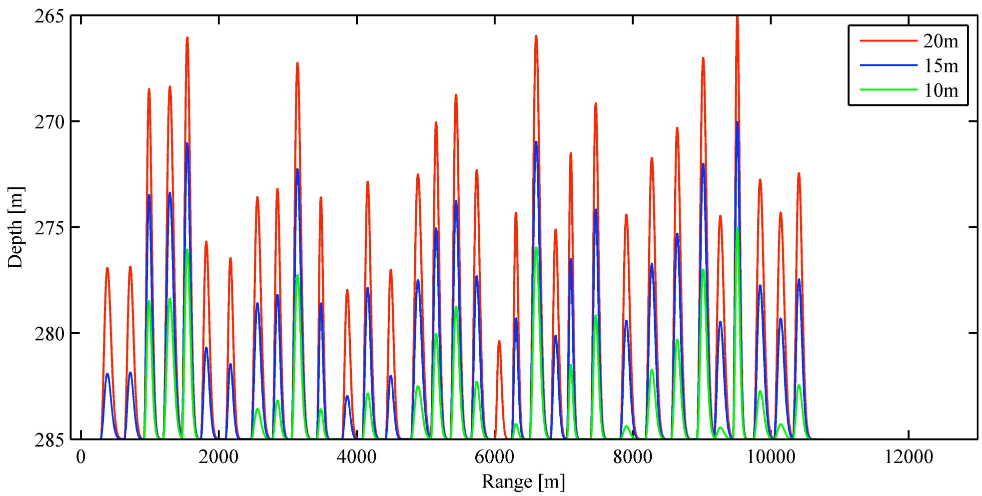

Figure 1: Bathymetry of testcases.

Figure 2 shows $\zeta(m) = (1/N_xN_z) \sum_{nxnz}| I^{+\infty}_e - I^{+}_m|$ for cases A, B, C (with and without the evanescent mode 5), and case D. $I^{+\infty}_e$ is the intensity of the exact forward propagating field (includes coupling with backward propagating field to infinite order) and I^{+}_m is the intensity of the forward going field that contains the coupling with backward propagating field to the mth order. In case A there is rapid convergence of the binomial series for the effective coupling (C_{eff}) between the forward and backward propagting acoustic fields for both the 4 mode and the 5 mode case. The presence of mode 5 does not significantly affect the convergence of the binomial series for C_{eff}. While the convergence of C_{eff} for case B takes a different path than case A, it too rapidly converges. Also, like case A the presence of mode 5 does not significantly affect the convergence of the expansion series for C_{eff}. An important observation for both cases A and B is that $\zeta(m) < \zeta(m\text{-}1) < \zeta(m\text{-}2) \cdots < \zeta(1) < \zeta(0)$. However, for case C, while $\zeta(1) < \zeta(0)$, $\zeta(m)$ does not decrease sequentially with *m*. Further, convergence with and without mode 5 has a different character and for both cases the convergence of the expansion for C_{eff} is significantly slower as compared to cases A and B. The slower convergence is clearly related to the larger inhomogeneities that create a larger coupling of $\mathbf{R}^{-\infty}$ on $\mathbf{R}^{+\infty}$ where $\mathbf{R}^{-\infty}$ and $\mathbf{R}^{+\infty}$ are the asmypotic mode amplitude vectors. With the exception of $\zeta(3) < \zeta(5)$, $\zeta(m)$ uniformly decreases for case D. However the convergence for case D is at a much slower rate than for cases A, B, and C. It was found that the coupling of mode 4 to the other modes(especially mode 3) as it transitions from

propagating to evanescent is the main reason for the slower convergence of the perturbation series for C_{eff}. Because this type of coupling occurs at multiple locations in the inhomogeneous region, a type of resonance phenomena is created. In nuclear theory resonances, bound states, and composite particle states in an effective potential cause perturbation series, such as the Born series, to have very slow convergence rates or to diverge, and methods to obtain convergent perturbation series or to increase the rate of convergence have received considerable attention.

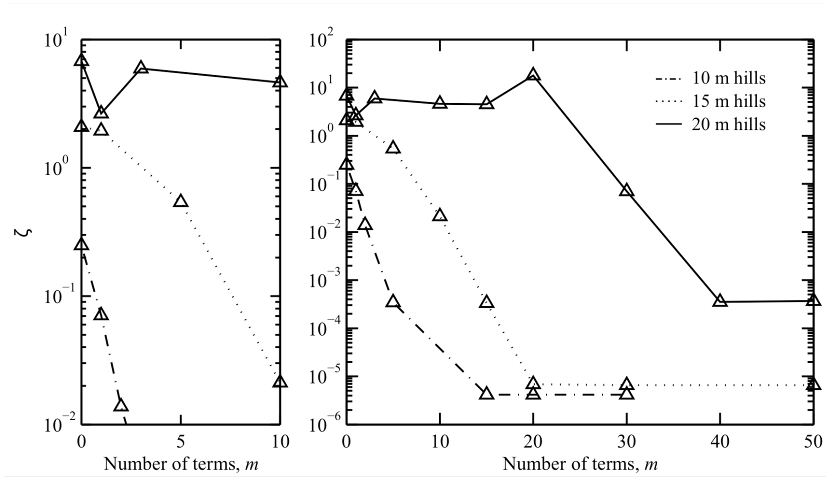

Figure 2: The convergence of ζ as a function of m for cases A-C with and without evanescent mode and for case D. The triangles represent cases without an evanescent spectrum and x represent cases that include an evanescent spectrum.

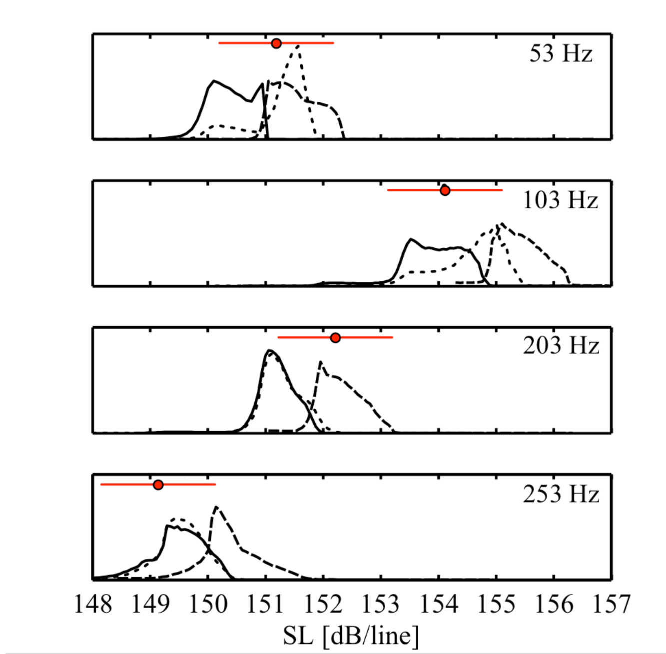

Figure 3: Comparison of source level marginal distributions to ground truth source level values (red dots with line). The dotted, dashed, and solid lines are for environmental representations 1, 2, and 3, respectively.

(2) Figure 3 shows the marginal distributions for the source levels (dB/line rel 1 μPa at 1 m) for the towed source data sample measured on a 52-element array during SW06. These comparisons in part provide a validation check for the marginal distributions of the geoacoustic parmaeters (see Ref. 2) because the reported source levels (SL) were measured during the experiment and a conservative

uncertainty was provided by the manufacturer of the recording hydrophone. Namely, the SLs are one of the parameters where strong ground truth exist. The SL distributions are shown for three different geoacoustic representations for the four source frequencies. Superimposed on the marginal distributions are the measured source levels made on a High Tech Inc (HTI) 90 hydrophone positioned 1 m from the J-15-1 towed source. These mean values were determined over the 33 minute time interval during which the towed data sample was collected. The uncertainty of the measured source levels (± 1 dB) were taken from the manufacturer specification sheet for the hydrophone sensitivity. First, one should note that the constraint estimates, the selection of the error function, and the assumptions made for the prior distributions P(**H**) or equivalently the specification of the model space were perhaps reasonable choices in the sense that the uncertainties of the marginal distributions and those of the reported source levels overlap. Second, even though the marginal distributions are sensitive to the differences in the three geoacoustic representations, the magnitude of the difference of the mean values of the marginals and the reported mean values of the SL are all within the uncertainties of the marginals and the reported source levels. This is due in large part because of the hardness of the surface of the seabed.

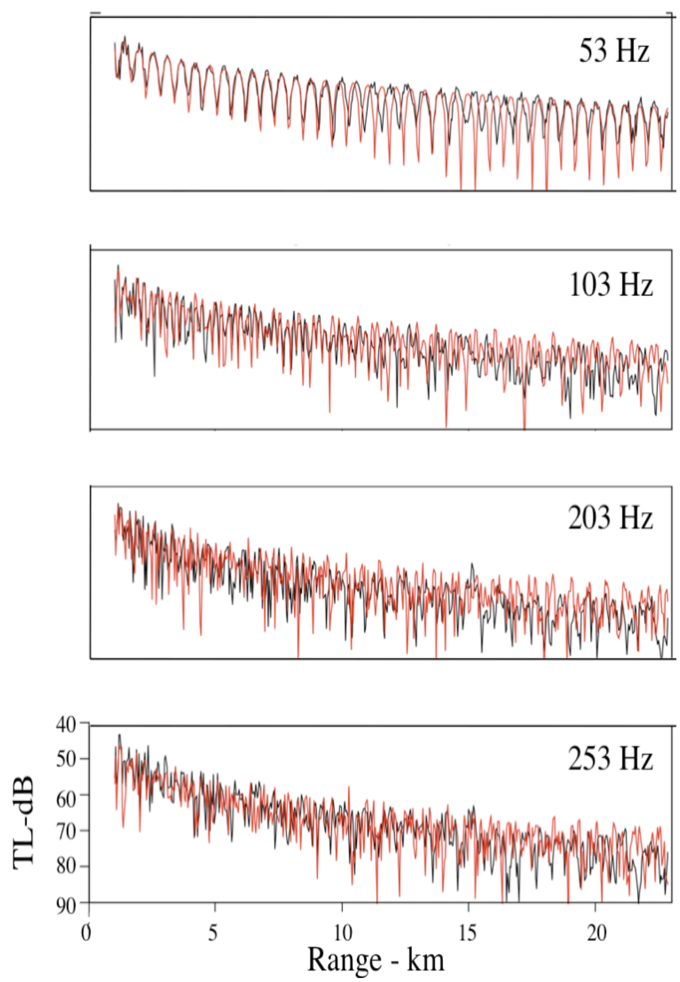

Figure 4: Comparison of modeled transmission loss (red) with optimized geoacoustic parameters and measured transmission loss (black) (optimized source level – measured received level).

Figure 4 shows comparisons of modeled and measured transmission loss at the four J-15-1 tow frequencies. The soiurce track used to validate the maximum entropy method in Fig. 3 was approximately a 3 km section of the full 25 km segment over which a geoinversion approach was

applied to extract estimates of values for geoacoustic parameters. The source levels were also inversion parameters, however, the upper and lower bounds were determined from the ground truth measurements and the prior assumption of a 2 dB uncertainty. The modeled transmission loss in Fig. 4 are those obtained using the optimized geoacoustic solution in a range-independent normal mode model. The inversion solution is similar to what has been previously reported in Refs. 2-3. A notable difference is that the attenuation in the first sediment layer could be determined (non-flat marginal distributions) because of the long range data employed in the analysis. Fig. 4 suggests that the attenuation was slightly underestimated as the modeled transmission loss beyond 20 km is about 3 dB too low. It is of interest to observe that the coherent structure of the measured transmission loss is reasonably well reproduced in the modeled transmission loss out to about 20 km (~ 300 water depths). This result may be fortutious as the non-linear internal wave activity was low during the time of the measurement.

IMPACT/APPLICATIONS

One potential impact of this research is that these studies may assist in understanding how to optimally combine advance propagation models (non-separable and 3-D) and information inference methods as one proceeds to study ocean waveguides with increasing complexity and inhomogeneity.

TRANSITIONS

The combined study of statistical inference and the effects of seabed layering is expected to relate propagation statistics to physical mechanisms on continental shelf and slope environments. The knowledge of such statistics and their relationship to the physics of the propagation may be useful for sonar applications in continental shelf and slope environments.

RELATED PROJECTS

Related research projects include applying maximum entropy to problems in cosmology.

REFERENCES

1. D. P. Knobles and J. D. Sagers, "A nonlocal effective operator for coupling forward and backward propagating modes in inhomogeneous media," to appear in J. Acoust. Soc. Am Nov. 2011.
2. D. P. Knobles and J. D. Sagers, "Maximum entropy approach for statistical inference in an ocean acoustic waveguide," under review in J. Acoust. Soc. Am.
3. D. P. Knobles, P. S. Wilson, J. A. Goff, and S. E. Cho, "A seabed acoustics experiment on a sand ridge on the New Jersey continental shelf," J. Acoust. Soc. Am. **124**, EL151-EL156 (2008).

PUBLICATIONS

1. D. P. Knobles and J. D. Sagers, "Maximum entropy approach for statistical inference in an ocean acoustic waveguide," under review in J. Acoust. Soc. Am.
2. D. P. Knobles and J. D. Sagers, "A nonlocal effective operator for coupling forward and backward propagating modes in inhomogeneous media," to appear in J. Acoust. Soc. Am Nov. 2011.